A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

NeoBiota 103: 85–106 (2025)
DOI: 10.3897/neobiota.103.157791

Research Article

Estimating relative density of an invasive ungulate in a biodiversity hotspot using drone-based thermal video surveys

Julia Witczuk[1], Stanisław Pagacz[1], Romain Alliod[2]

1 Museum and Institute of Zoology, Polish Academy of Sciences, Twarda 51/55, 00-818 Warsaw, Poland
2 Ecotone NC SARL, 8 rue du capitaine bois, 98800 Nouméa, New Caledonia (Fr)
Corresponding author: Julia Witczuk (jwitczuk@miiz.waw.pl)

Abstract

New Caledonia's unique terrestrial habitats – primarily mountain rainforest and sclerophyll forest – face significant threats from invasive ungulates, particularly Javan deer (*Rusa timorensis*), introduced in the 19th century and now widespread. Since deer are an important game and food source for local communities, the management strategy aims to mitigate their detrimental impact on ecosystems while maintaining populations at levels that continue to support hunting. To achieve these objectives, effective and reliable population monitoring methods are essential. Unmanned aerial vehicles (drones) equipped with thermal sensors represent a potentially superior alternative to conventional ground-based methods for ungulate inventories, particularly in remote and difficult-to-access areas. In this study, we explored the feasibility of using a rotor-wing drone and a thermal camera to estimate the relative density of Javan deer in two protected areas: Domaine de Déva (7,319 ha) and Parc provincial des Grandes Fougères (8,098 ha). Visual line-of-sight flights were conducted after sunset at altitudes of 80 and 100 m above ground level, with the camera fixed at 40° or 0° angles. In Déva, we surveyed 10 sampling blocks, and in Grandes Fougères, 4 blocks (each ranging from 56 to 92 ha). In the predominantly open savanna area of Déva, the estimated relative population density was 116 deer/km^2 (SE = 26.8), with some blocks exceeding 400 deer/km^2. In contrast, in the dense canopy rainforest of Grandes Fougères, the relative density was 7 deer/km^2 (SE = 2.8), with a local maximum of 18 deer/km^2. Differences in deer counts between consecutive flights over the same blocks (with time gaps of less than 100 minutes) were minor, demonstrating that drone surveys are highly repeatable – an essential quality for a reliable population monitoring program. To detect a 25% population reduction with a statistical power of 0.8, surveying 10 sampling blocks was sufficient in the high deer density savanna area, whereas approximately 28 blocks would be required in the rainforest. The logistics of drone operations were relatively straightforward in the savanna; however, in the rainforest, we encountered practical difficulties, including a limited number of suitable take-off sites and restricted visibility due to the dense canopy cover. Despite these obstacles, the method proved to be an effective and efficient approach for monitoring deer populations in the challenging landscapes of New Caledonia.

Key words: Javan deer, New Caledonia, Rusa deer, *Rusa timorensis*, thermal infrared camera, unmanned aerial vehicle, wildlife monitoring, wildlife survey

Academic editor: Sandro Bertolino
Received: 3 May 2025
Accepted: 14 September 2025
Published: 10 October 2025

Citation: Witczuk J, Pagacz S, Alliod R (2025) Estimating relative density of an invasive ungulate in a biodiversity hotspot using drone-based thermal video surveys. NeoBiota 103: 85–106. https://doi.org/10.3897/neobiota.103.157791

Introduction

Biodiversity loss is currently one of the primary challenges in nature conservation. It is driven by habitat degradation, climate change, as well as competition and predation by alien invasive species (Vitousek et al. 1997; Lefeuvre 2006; Kingsford et al. 2009; IPBES 2019). The negative impact of non-native animals is particularly pronounced on isolated oceanic islands (Courchamp et al. 2003; Russell and Kueffer 2019). Their unique, predominantly endemic vegetation, which often evolved without pressure from large mammalian herbivores and therefore did not develop adequate defense mechanisms, is especially vulnerable to the presence of human-introduced domesticated or wild ungulates (Bowen and Van Vuren 1997). Moreover, in the absence of natural predators, herbivore populations can expand rapidly, posing an increasing threat to island ecosystems. Consequently, controlling invasive herbivores is a crucial conservation priority on islands (Courchamp et al. 2003).

New Caledonia is a Pacific archipelago located about 1,500 km east of Australia. It is characterized by exceptional biodiversity and a high number of endemic species. Of the more than 3,300 native vascular plant species found there, 75% are endemic (Morat 1993; Isnard and Jaffré 2024; Munzinger et al. 2025), and the archipelago is considered one of the most important biodiversity hotspots on Earth (Myers 1988; Myers et al. 2000). The most valuable terrestrial habitats of Grande-Terre, the archipelago's largest island – tropical rainforests (83% of endemic species) and dry sclerophyll forests (57% of endemic species) – are severely threatened by mining, logging, fire, agriculture (cattle grazing), and invasive species (Mittermeier et al. 2004; Isnard and Jaffré 2024). While rainforests still cover much of the hard-to-reach inland areas at higher elevations, the small remnants of the sclerophyll forests that have survived, scattered within savannas along the west coast, occupy only 2% of their original area (Bouchet et al. 1995).

Javan deer (*Rusa timorensis*), also known as Rusa deer, were introduced to Grande-Terre in the 1870s. Due to their high adaptability, as well as the lack of competitors and predators, the species quickly spread throughout the island. Currently, their abundance is estimated at several hundred thousand individuals (Barrière and Fort 2021), with the highest densities recorded along the west coast of the island (de Garine-Wichatitsky et al. 2004). The species is now listed as one of the major priority invasive species (Conservatoire d'espaces naturels de Nouvelle-Calédonie 2017). The highly negative impact of deer on the endemic flora is observed both in the remnants of the sclerophyll forest (Bouchet et al. 1995; Gargominy et al. 1996; de Garine-Wichatitsky and Spaggiari 2008; Mansourian et al. 2018) and in the mountain rainforests (Le Bel et al. 2001; Tron et al. 2024). Deer destroy endemic plant species and impede forest regeneration through browsing, debarking, and trampling. They also contribute to the spread of invasive plant species by actively dispersing their seeds (de Garine-Wichatitsky and Spaggiari 2008). Severe overgrazing causes soil erosion and negatively affects water resources on the island (Tramier et al. 2021). Additionally, local farmers are concerned about the damage caused by deer to pastures and agricultural crops (Barrière and Fort 2021). Although the impact of Javan deer on the island's ecosystems is undoubtedly negative, they also represent a significant source of game meat for local communities, and deer hunting is an important part of their culture (de Garine-Wichatitsky et al. 2004). For this reason, the species cannot be treated solely as a pest to be eradicated from the island. Instead, it is necessary to manage the population in a way that minimizes its negative effects on biodiversity and agriculture while maintaining it at a level that preserves its social significance. Achieving such goals requires effective and reliable methods of population monitoring.

The Javan deer population management strategy adopted in New Caledonia focuses control efforts on 10 designated priority areas that are particularly valuable for biodiversity and provide essential ecosystem services, such as those critical to the water cycle (Conservation International and Conservatoire d'espaces naturels de Nouvelle-Calédonie 2016). In three of these areas, regular monitoring and intensive professional deer control have been planned within the framework of the PROTEGE project (Pacific Community 2025). Based on previous experience with deer surveys in New Caledonia (de Garine-Wichatitsky and Saint-Andrieux 2003; Roques-Rogery 2008) and the results from tests conducted under the invasive ungulate control plan launched in 2008 (Barrière and Fort 2021; Fort and Barrière 2021), the strategy recommends monitoring populations using indirect methods that measure deer impact on the forest, along with direct animal observations to estimate abundance indices and identify areas of deer concentration.

Due to the nocturnal activity of Javan deer and the limited access to the survey areas, thermal camera observations conducted from unmanned aerial vehicles (drones) are considered the most promising new monitoring method. Previous studies in temperate forests have shown that detecting large mammals in drone-acquired thermal imagery is possible even in relatively dense conifer stands (Witczuk et al. 2018). Tests over captive deer enclosures have further demonstrated that this approach can provide accurate animal counts (Beaver et al. 2020; McMahon et al. 2021; Zabel et al. 2023). The method has also proven reliable under natural conditions, with drone surveys producing consistent results when conducted alongside other deer density estimation methods – such as pellet-group counts and camera trapping (McMahon et al. 2022; Baldwin et al. 2023; Finnegan et al. 2024). Moreover, drone flights in difficult mountainous terrain have been reported to be much more feasible and effective than ground-based observational surveys (Trinh-Dinh et al. 2024).

The purpose of this study was to test whether drone-based thermal video surveys could be an effective method for monitoring the Javan deer population in the challenging landscapes of New Caledonia. Following preliminary flights to determine optimal flight parameters, we tested the method in two of the island's main habitat types – open savanna and dense canopy rainforest – and aimed to establish a methodological foundation for future deer inventories in New Caledonia and similar environments.

Methods

Study areas

The research was conducted on Grande-Terre (16,372 km^2), the main island of New Caledonia. The island has a tropical climate with two seasons: a dry season (from mid-April to mid-November) and a rainy season (from mid-November to mid-April) (Fotsing and Dumas 2021). Average monthly temperatures range from 20 to 26 °C, and monthly precipitation varies from 55 mm in October to 271 mm in March (World Bank 2025). The island is sparsely populated, with an average population density of about 15 inhabitants per km^2. There are no native mammals on the island except bats. Besides the invasive deer and feral pig (*Sus scrofa*), the island is also inhabited by domestic cattle, goats, and horses.

The choice of the study areas was strongly influenced by COVID-19 pandemic restrictions, as most of the mountain rainforest priority zones designated for deer management were inaccessible due to the lockdown.

The first stage of the research involved test flights to establish the optimal flight altitude and camera angle. These were conducted at a private hunting and cattle farm, La Cotonnière, Boulouparis (21°51.23'S, 165°54.65'E). The property (350 ha) features hilly terrain with extensive plains and woodlands. For the test flights, we chose flat, grassy areas with numerous deer.

The survey flights to estimate relative deer densities were conducted in two protected areas: Domaine de Déva and Parc provincial des Grandes Fougères (Fig. 1). The survey areas were selected to represent two different ecosystems of the island.

Domaine de Déva (21°33.55'S, 165°20.05'E) is a 7,319 ha area located on the west coast of the island. The terrain is hilly, with elevations ranging from 0 to 383 m a.s.l. and a mean slope of 12°. The area is dominated by savanna – grasslands and shrub with discontinuous tree cover (Figs 1, 2). Sparse forests include the largest remaining patches of sclerophyll forest in New Caledonia.

The Parc provincial des Grandes Fougères (21°36.55'S, 165°45.15'E) is situated approximately in the middle of the island's central mountain range. The park covers 4,546 ha, but with a 700 m buffer around the park boundaries included, our resulting study area was 8,098 ha. The elevation ranges from 157 to 718 m a.s.l., with a mean slope of 21°. The area is dominated by tropical rainforest, interspersed with patches of shrubs and grassland savannas (Figs 1, 2).

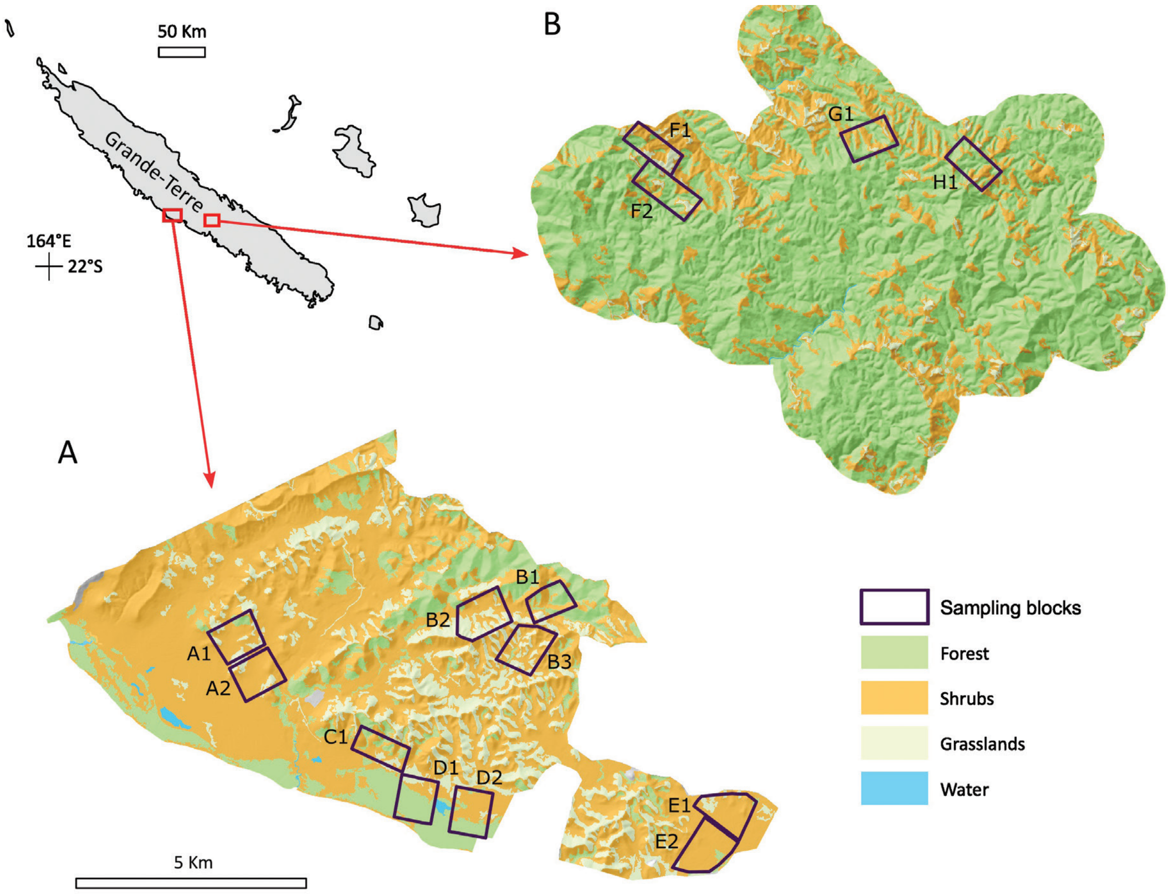

Figure 1. Land cover of the two study areas and locations of sampling blocks for Javan deer (*Rusa timorensis*) thermal drone surveys in New Caledonia: Domaine de Déva (**A**) and Parc provincial des Grandes Fougères (**B**); both areas are shown at the same scale.

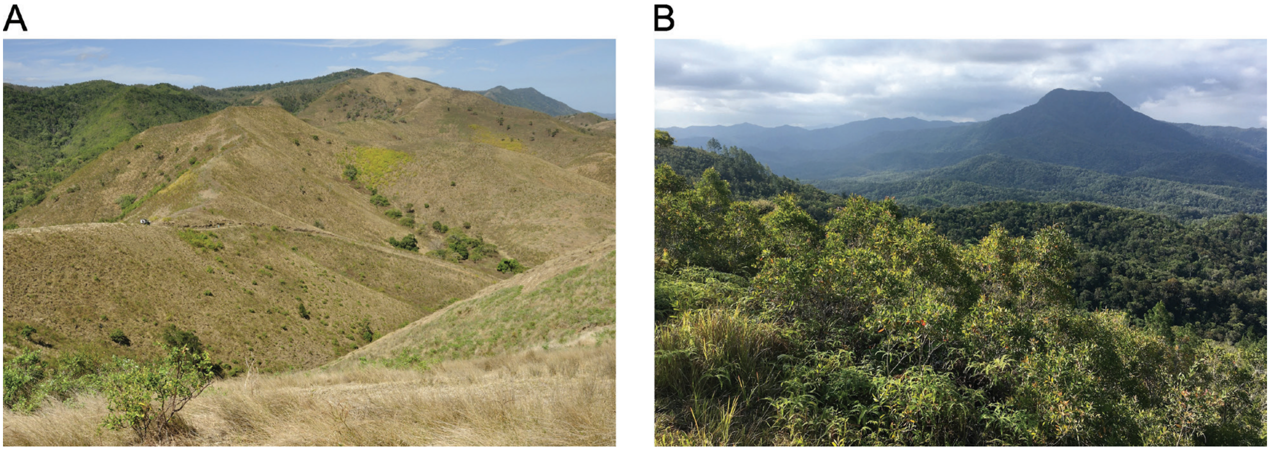

Figure 2. Landscapes of the two study areas for Javan deer (*Rusa timorensis*) thermal drone surveys in New Caledonia: Domaine de Déva (**A**) and Parc provincial des Grandes Fougères (**B**).

Drone and sensor

The flights were conducted using a Matrice 300 RTK quadcopter (DJI, Shenzhen, China). The drone is powered by two lithium polymer batteries (capacity 5,935 mAh), enabling a flight endurance of up to 40 minutes. The maximum flight speed is 23 m/s, and the drone is resistant to winds up to 12 m/s. The take-off weight is 9 kg, including two batteries, a gimbal, a camera, and a parachute. Detailed drone specifications can be found on the manufacturer's website (https://enterprise.dji.com/matrice-300).

The drone was equipped with a hybrid RGB/thermal infrared camera, the Zenmuse H20T (DJI, Shenzhen, China). The thermal component of the camera featured an uncooled, microbolometer focal plane array detector (640 × 512 pixels, 12 μm pixel pitch, spectral range 8–14 μm) with a 13.5 mm focal length, f/1.0 lens. The camera was mounted on a downward gimbal, with the camera's horizontal axis aligned perpendicularly to the flight path. Video files (30 Hz) in mp4 format were saved on an SD card; the recorded scenes were also viewed in real time on the drone's remote controller. Georeferencing data and flight parameters were stored in STR (SubRip Text Subtitle) files.

Establishing optimal flight altitude and camera angle

The quality of video data acquired by drones strongly depends on the flight altitude above the ground and the angle of the camera. Both of these variables affect the ground sampling distance (GSD, i.e., pixel size) and the size of the camera's instantaneous field of view (video footprint) (Burke et al. 2019). The lower the flight altitude, the smaller the GSD, improving the ability to distinguish small details in the imagery. However, this comes at the cost of reducing the image footprint size, and thus survey efficiency, as more time is required to cover the same area (Fig. 3). To ensure high detectability and accurate identification of animals in thermal imaging, the thermal signature of an animal should be at least 10 pixels long (Witczuk et al. 2018; Burke et al. 2019). As the average body length of Javan deer is between 130 and 170 cm, the maximum acceptable GSD should be 13 cm. Because of the variability in GSD caused by the camera angle and topography, we applied a conservative rule that the GSD should not exceed 10 cm.

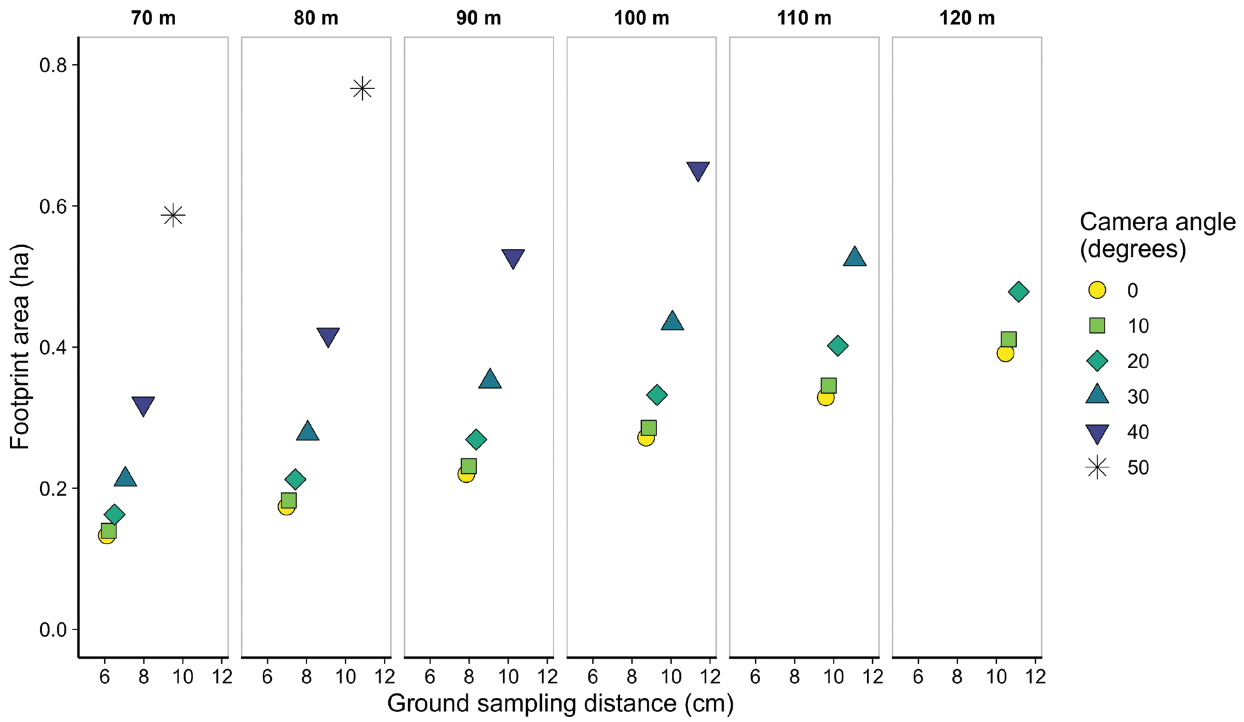

Figure 3. Ground sampling distance (at the center of the camera's field of view) and footprint area (camera's instantaneous field of view) for a range of flight altitudes (70–120 m) and camera angles (0–50°). For some combinations of altitudes and angles, the resulting ground sampling distances exceeded the 5–12 cm range and are not shown. A combination of 80 m altitude and a 40° camera angle provides a ground sampling distance of < 10 cm while maximizing the footprint area.

To assess the differences in video quality acquired at a range of altitudes (70–120 m) and camera angles (0–50°), we conducted test flights at La Cotonnière farm in May and September 2021 (Fig. 4). Recorded videos were visually inspected, and each altitude–camera angle combination was rated based on the level of detail enabling easy detection and identification of deer while maximizing the footprint area. From this analysis, we established that the optimal parameters for survey flights were 80 m altitude above ground level and a 40° camera angle. These settings result in a GSD resolution of ~9 cm (in the center of the camera's field of view) and a filmed strip width of about 76 m (calculated based on the formulas provided by Burke et al. 2019).

During survey flights over the rainforest, we also collected data using a 0° camera angle (pointing directly downward) to enhance detection of animals obscured by trees. For these flights, altitude was increased to 100 m to maintain the desired GSD of ~9 cm. These alternative settings resulted in a narrower filmed strip width of 59 m.

Survey flight operation details

At Déva, flights were conducted from 23 to 25 September 2021, and at Grandes Fougères on 4 and 5 October 2021 (Table 1). The survey flights were carried out at night, from sunset (around 7 PM) to approximately 1 AM (NCT), as opportunistic observations indicated that deer become more active around sunset, when they emerge from forests to feed in adjacent grasslands, with activity decreasing after midnight. A similar activity pattern was observed in sambar deer (*Rusa unicolor*) introduced to Australia (Comte et al. 2022).

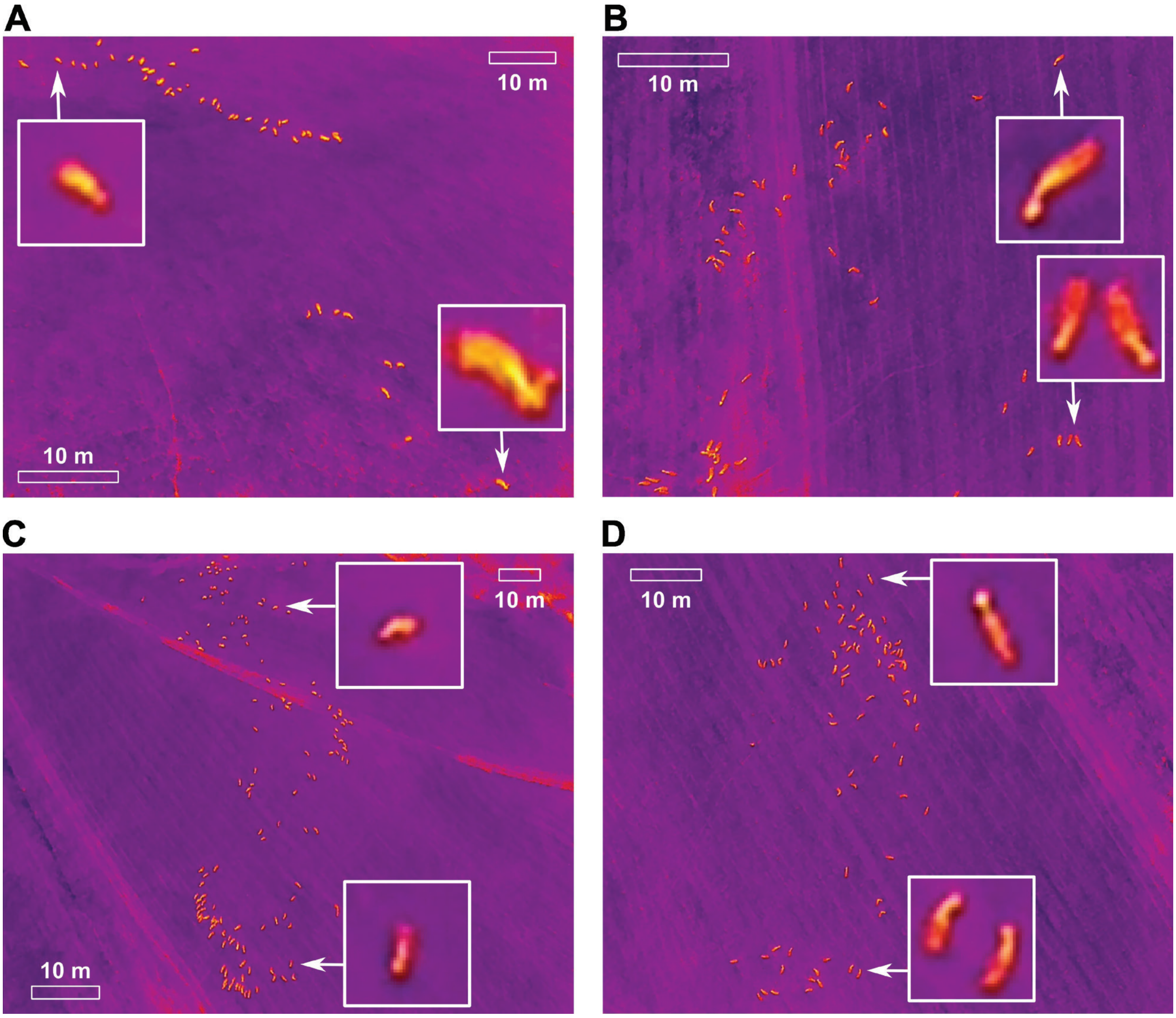

Figure 4. Video frames showing Javan deer (*Rusa timorensis*) thermal signatures captured by a drone at different altitudes and camera angles: 80 m, 50°, 44 individuals (**A**); 80 m, 0°, 52 individuals (**B**); 120 m, 50°, 132 individuals (**C**); 120 m, 0°, 79 individuals (**D**). Insets show close-ups of selected thermal signatures from the top and bottom parts of the images (note the different scales in the top and bottom sections of images recorded with a 50° camera angle). Videos were recorded during test flights at La Cotonnière farm, Boulouparis, New Caledonia, in May and September 2021.

At each study area, we selected suitable take-off sites for drone operations that offered vehicle access and clear visibility of the surrounding terrain to ensure flight safety and simplify logistics. Simultaneously, we aimed to choose locations that represented the full range of habitats occurring within the study area. Importantly, site selection was independent of the deer distribution.

In the Déva study area, we sampled a total of 10 blocks, which ranged in size from 56 to 92 ha (mean 77 ha). The blocks were reached from five take-off locations. In the Grandes Fougères study area, we sampled four blocks (63–84 ha, mean 70 ha), reached from three take-off sites (Figs 1, 5).

The size of the sampling blocks was determined by two constraints: the requirement for visual line-of-sight flights – the drone had to remain within 1,800 m of the operator (as per our derogation) – and the need to retain at least 20% of the drone's battery after surveying a sampling block to ensure a safe return. Given the variability in take-off site conditions (openness, visibility, and topography), the number, location,

Table 1. Details of flights and the number of Javan deer (*Rusa timorensis*) detected during thermal drone surveys in New Caledonia. Differences in the surveyed area between flight repetitions in the Grandes Fougères are due to varying flight altitudes (80 m and 100 m) and camera angles (40° and 0°) used for each flight.

Study area	Sampling block	Number of flights	Date	Start times	Area surveyed (ha)	Detected individuals
Déva	A1	2	25.09.2021	19:02, 20:38	85, 85	47, 64
	A2	2	25.09.2021	19:32, 21:07	84, 84	66, 73
	B1	2	24.09.2021	19:04, 21:02	60, 60	44, 56
	B2	2[†]	24.09.2021	19:37, 21:29	93, 44	237, 154
	B3	2	24.09.2021	20:22, 21:56	85, 85	211, 191
	C1	2	25.09.2021	22:25, 22:55	70, 70	121, 120
	D1	2	23.09.2021, 24.09.2021	23:27, 0:42	79, 79	17, 19
	D2	2	24.09.2021	0:15, 1:11	83, 83	28, 33
	E1	1	23.09.2021	19:27	84	77
	E2	2	23.09.2021	18:52, 20:14	88, 88	98, 68
				Total	811, 678	946, 778
Grandes Fougères	F1	2	04.10.2021	19:03, 20:12	57, 45	10, 8
	F2	2	04.10.2021	19:36, 20:42	75, 53	2, 2
	G1	2	05.10.2021	18:55, 19:23	62, 44	0, 1
	H1	2	05.10.2021	0:32, 1:03	58, 48	4, 4
				Total	252, 190	16, 15

[†]Second flight incomplete

and flight paths of sampling blocks were planned during fieldwork to maximize coverage and minimize the risk of losing communication with the drone.

The flight paths within the sampling blocks had the form of parallel transects (Fig. 5) ranging in length from 0.2 to 1.4 km (mean 1.1 km, SD = 0.19 km). Each block contained 6 to 11 transects. The spacing between non-overlapping filmed strips was about 10 m. The total length of all transects was 106.5 km in Déva and 32.2 km in Grandes Fougères.

For most of the sampling blocks (12 out of 14), surveys were repeated twice (Table 1). However, due to technical problems at one of the remaining blocks (Déva B2), the second survey was incomplete, and one block (Déva E1) was surveyed only once.

Survey flights over a single block lasted between 18 and 25 minutes, excluding the time required for the drone to travel from the take-off site to the sampling block and back. The interval between the first and second surveys ranged from 8 to 100 minutes (mean 54 minutes).

In Déva, both survey repetitions were conducted at an altitude of 80 m with the camera fixed at a 40° angle. In Grandes Fougères, the first survey was also conducted from 80 m at a 40° camera angle. However, since the area was mainly covered by dense canopy forest, the second survey was conducted with the camera fixed at 0° and at an altitude of 100 m to enhance animal detectability. The drone's speed ranged between 8 and 10 m/s.

The survey missions were programmed using Mission Planner software (ArduPilot) and flown autonomously, with only take-off and landing performed manually. Flight parameters and the drone's location were monitored by the pilot on a ground control station and the screen of the remote controller. Each block was intended to be surveyed using one pair of batteries; however, we assumed the mission would be interrupted and the drone returned to the take-off site if the battery charge dropped to 20%. During all flights, the drone was observed by a second person – the spotter.

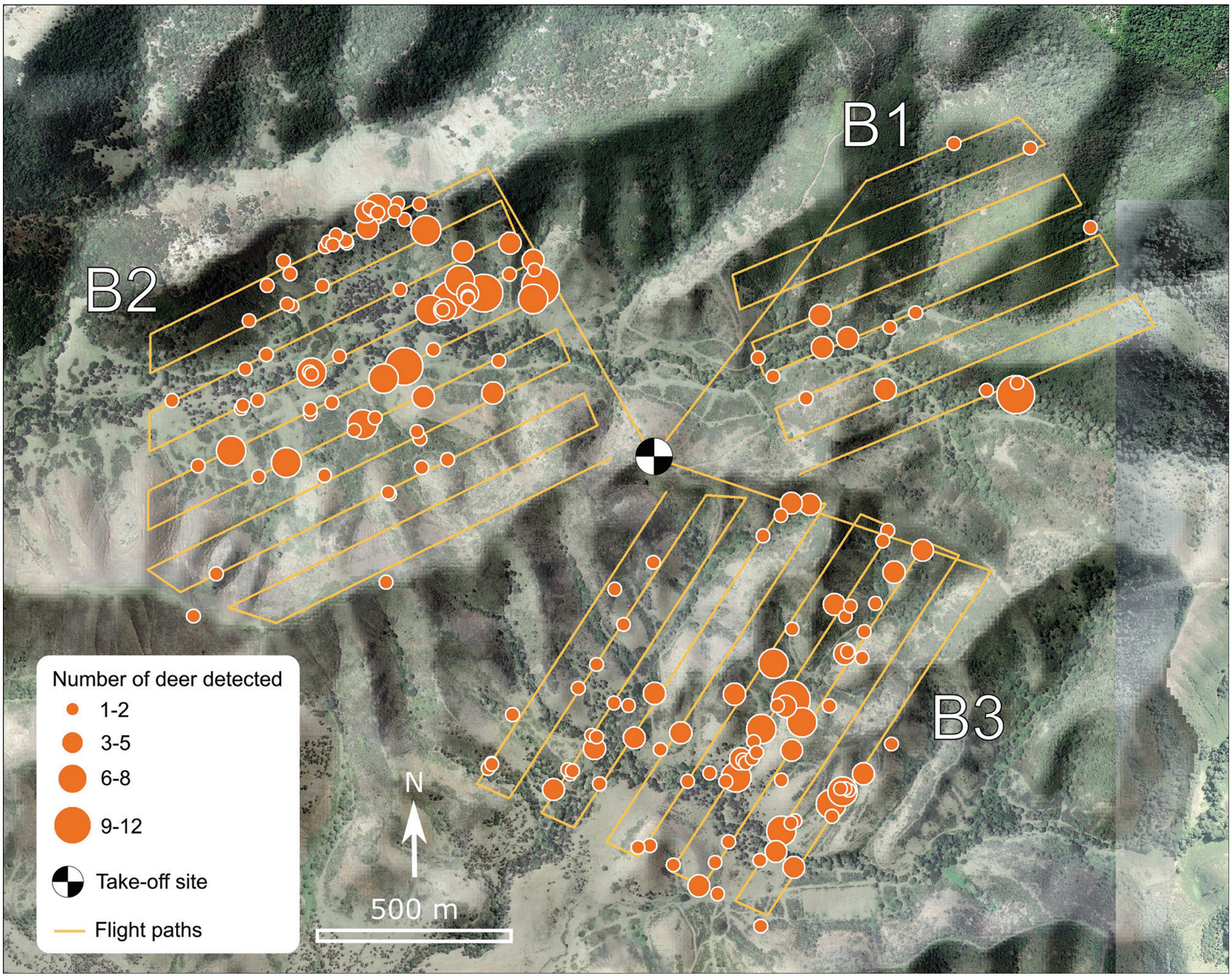

Figure 5. Distribution of Javan deer (*Rusa timorensis*) during the thermal drone survey in three sampling blocks (B1, B2, B3; first flight) at the Domaine de Déva study area, New Caledonia. Total number of deer detected: 44 (B1), 237 (B2), 211 (B3). Background image: Gouvernement de la Nouvelle-Calédonie / DITTT / Service topographique.

Video analysis

Videos were reviewed manually by two independent observers using the Full Motion Video (FMV) plug-in for QGIS (Raga 2021). This plug-in allows for the analysis and visualization of drone videos within a geographic information system (GIS) environment. FMV requires metadata compatible with the Motion Imagery Standard Board (MISB); however, the STR metadata generated by the H20T camera are not MISB-compatible. To overcome this, we developed a Python script to convert the STR files to the required format.

While reviewing files in FMV, when a deer or group of deer was detected, we marked its location, or the center of the group, by placing a point on the video display (signatures for which identification was uncertain were omitted). This action simultaneously created a corresponding point on the map layer, which was later saved in ESRI shapefile format. For each detection, we recorded the timestamp, number of animals, and observed behavior in an Excel spreadsheet. Behavior (generalized at the group level) was classified into one of four categories: 1) running, 2) walking, 3) moving (i.e., remaining in the initial location but changing body position), or 4) still.

Data analysis

For both study areas, Déva and Grandes Fougères, we calculated the relative deer densities for the first and second surveys as:

$$\mathrm{D_r} = \frac{\sum n_i}{\sum A_i} \quad (1)$$

where n_i is the number of deer detected in sampling block i, and A_i is the surveyed area within block i. The surveyed area was determined as the product of the total length of all transects within a block and the filmed strip width.

To calculate overall deer density for each study area, we summed the deer counts from both survey repetitions and divided this total by the combined area surveyed across both repetitions. The standard error of the density estimates was obtained using nonparametric bootstrapping.

To quantify the variability in deer counts between two consecutive surveys within individual sampling blocks, we calculated the percentage of absolute change as:

$$\frac{|n_1 - n_2|}{n_1} 100\% \quad (2)$$

where n_1 and n_2 are the counts from the first and second surveys in a given sampling block.

Variability in counts among the sampling blocks was assessed by comparing the mean counts from both surveys.

To estimate deer densities in various habitats, we assigned each detection to a land cover class (forest, shrubs, grassland) in QGIS using a digital land cover dataset (Gouvernement de la Nouvelle-Calédonie and Observatoire de l'Environnement en Nouvelle-Calédonie 2019).

We explored the power to detect a population trend, i.e., a significant difference in relative density estimates between two hypothetical time points t_1 and t_2, by simulating mean densities for t_1 and t_2 and comparing them using a one-sided *t*-test at a 0.05 alpha level. We focused on detecting population reduction, as this is the goal of the species management plan. The mean population densities for t_1 and t_2 were sampled from a normal distribution across a range of the number of sampling blocks (10–40) and various levels of potential population decline (10–30%). For t_1, we used the relative deer density and standard deviation derived from our field data. Means for t_2 reflected the chosen levels of decline, with standard deviations decreasing proportionally to density (i.e., we assumed equal coefficients of variation: CV = SD/mean at both time points t_1 and t_2). Calculations were carried out using the Emon package in R (Barry and Maxwell 2017; R Core Team 2025).

Permits

A derogation document issued by the Direction générale de l'aviation civile (DGAC) granted us the following:

- Authorization to conduct flights for the acquisition of thermal imaging data,
- An exemption to fly at night at an altitude of up to 120 m above ground and up to 250 m in the event of a communication loss with the drone (Return-To-Home procedure),

- A horizontal distance waiver allowing flights up to 1,800 m from the pilot.

We followed all safety procedures applicable within the control zone (CTR) of the Poé aerodrome in the Déva area. These procedures – including notifying flight control staff at the beginning and end of drone flights, monitoring the air frequency via VHF radio, and other standard practices – were carefully implemented throughout all flight missions.

Permits to operate the drone within the protected areas of Déva and Grandes Fougères were issued by the Province Sud authority. Permits for conducting work and travel during the COVID-19 lockdown were issued by the Haut Commissariat de Nouvelle-Calédonie.

Results

At the Déva study site, we detected 946 Javan deer within a surveyed area of 811 ha during the first flight and 778 individuals within 678 ha during the second flight (Table 1). The largest group was 14 individuals (mean group size = 2); however, many groups were located close to one another, and the definition of a "group" was somewhat arbitrary (Fig. 6A). Estimates of relative deer density (the number of detected individuals per km^2 of surveyed area) were similar for the first and second surveys: 117 and 115 deer/km^2, respectively. The overall estimate calculated from both surveys was 116 deer/km^2 (SE = 26.8).

At the Grandes Fougères study area, we detected 16 individuals over a surveyed area of 252 ha during the first flight and 15 individuals over 190 ha during the second flight. These were mainly solitary animals; only in two cases did we observe groups of two and three individuals (Fig. 6B). As in the Déva study area, the estimated relative densities were similar between the two consecutive surveys: 6 deer/km^2 in the first and 8 deer/km^2 in the second. The overall estimate from both surveys was 7 deer/km^2 (SE = 2.8).

The differences in the number of deer detected between two consecutive surveys within individual sampling blocks ranged from 1 to 30 individuals in Déva (excluding counts for block B2, for which the second survey was incomplete) and from 0 to 2 individuals in Grandes Fougères (Table 1). The differences, expressed as the percentage of absolute change between counts, were positively correlated with the time gap between the two surveys of a given block ($R = 0.64$, $p = 0.02$).

Variability in counts among the sampling blocks was substantial (Fig. 5), with mean counts (based on two consecutive surveys) ranging from 18 to 201 individuals in Déva and from 0.5 to 9 individuals in Grandes Fougères.

Relative deer densities varied across land cover classes (Table 2). In Déva, the lowest density was observed in forested areas – 61 deer/km^2. In contrast, densities were significantly higher in open habitats, with 127 deer/km^2 in shrubs and 130 deer/km^2 in grasslands. A similar pattern was observed in Grandes Fougères, where the density in forested areas was 3 deer/km^2, compared to 7 deer/km^2 in shrubs and as high as 23 deer/km^2 in grasslands.

We did not observe any animal response to the presence of the drone – in 94% of cases, the detected animals remained completely still or only changed body posture (typically by moving their heads) while staying in the same location. Only 4% of detections involved walking animals, and 2% involved animals that were running.

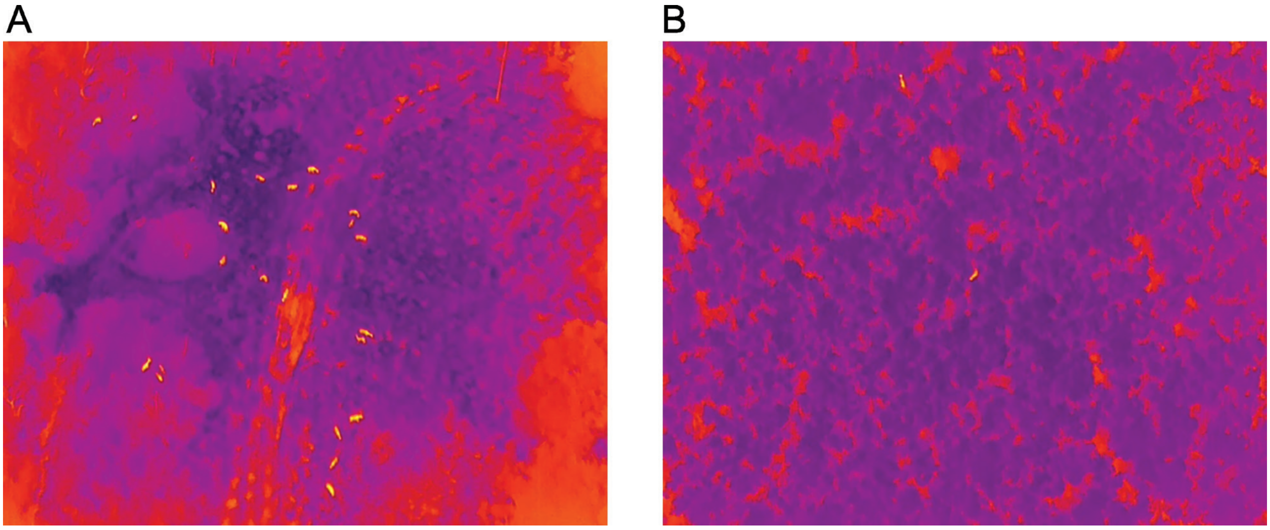

Figure 6. Video frames from thermal drone surveys in New Caledonia showing 22 Javan deer (*Rusa timorensis*) detected in Domaine de Déva on 23 September 2021 at 18:54 (flight altitude: 80 m, camera angle: 40°) (**A**), and two Javan deer detected in Parc provincial des Grandes Fougères on 4 October 2021 at 20:29 (flight altitude: 100 m, camera angle: 0°) (**B**).

Table 2. Relative densities of Javan deer (*Rusa timorensis*) from thermal drone surveys in two study areas in New Caledonia by land cover class. The number of detected individuals represents the total counts combined from two consecutive flights. The surveyed area represents the combined area covered during both flights.

	Domaine de Déva			Grandes Fougères		
Land cover class	Forest	Shrubs	Grassland	Forest	Shrubs	Grassland
Relative density (deer/km^2)	61.4	130.0	127.9	3.4	7.4	22.9
Detected individuals	181	1231	312	8	12	11
Area surveyed (km^2)	2.95	9.47	2.44	2.32	1.63	0.48

Power analysis indicated that, based on data collected from the 10 sampling blocks in Déva, a potential population decline of at least 25% could be detected with a power of 0.8. To detect a 20% decline with the same power, at least 15 blocks would be required. In contrast, the power to detect trends in the Grandes Fougères area was low – detecting a 25% population reduction would require sampling approximately 28 blocks (Fig. 7).

Discussion

The drone equipped with a thermal camera proved to be a highly effective tool for invasive Javan deer monitoring. However, the applicability of the method depends on the habitat that dominates the surveyed sites. In Déva – a study area with a mostly open, hilly savanna landscape – we detected hundreds of animals and, within a limited time, were able to gather high-quality data on the relative abundance and distribution of deer (Fig. 5). The estimated population density in this area (116 deer/km^2) was comparable to the highest estimates ever reported for the west coast of Grande-Terre based on spotlight counts (122 deer/km^2; Le Bel et al. 1999, as cited in Roques-Rogery 2008). Locally, the densities estimated in our study even exceeded 400 deer/km^2. Such high numbers are alarming and highlight

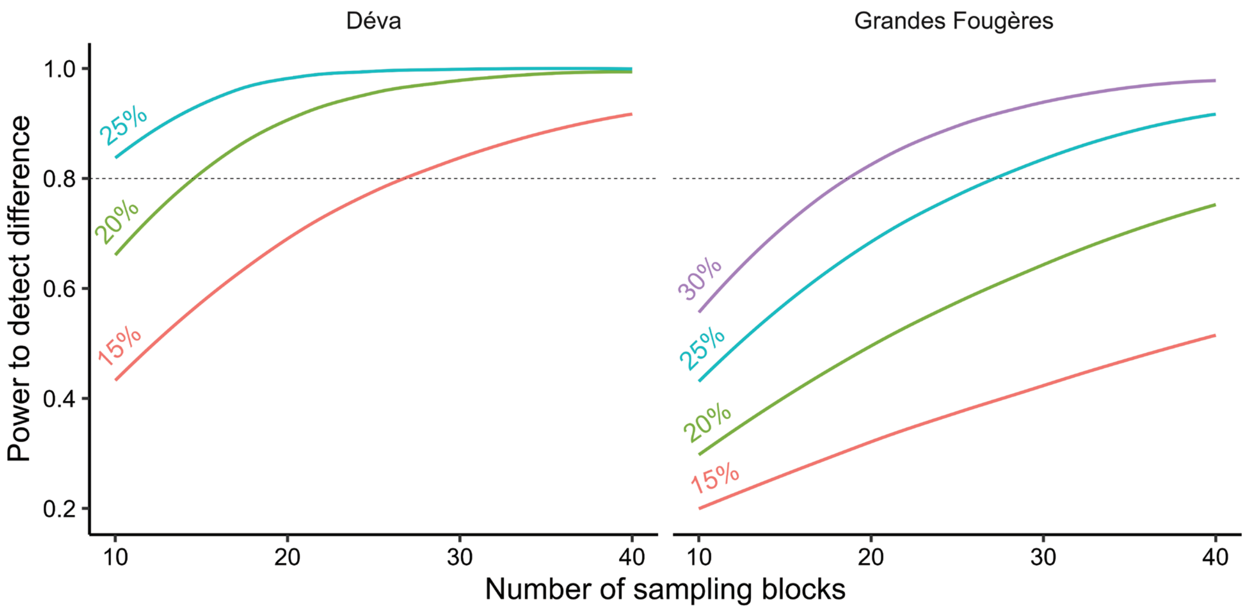

Figure 7. Power to detect a difference between two relative density estimates of Javan deer (*Rusa timorensis*) from thermal drone surveys in Domaine de Déva and Parc provincial des Grandes Fougères, New Caledonia, as a function of the number of sampling blocks and the magnitude of the potential population decline (solid color lines). The black dashed line indicates the minimum desirable power level (0.8).

the enormous scale of the problem that wildlife conservationists and managers in New Caledonia are facing.

In the second study area – Parc provincial des Grandes Fougères, covered mainly by dense rainforest – estimated deer densities were relatively low (7 deer/km^2), although locally reaching up to 18 deer/km^2. Similar Javan deer densities (1–17 deer/km^2) in New Caledonian rainforest were also observed in previous research using the pellet group-count method (Le Bel et al. 2001). In Grandes Fougères, the method showed certain limitations. The thick rainforest canopy potentially blocked the thermal signal of some animals, reducing detectability. Additionally, we encountered difficulties in finding suitable take-off sites from which to perform the flights. Trees often limited the observer's field of view toward the drone flight path and interfered with communication between the aircraft and the remote controller. Another limiting factor in this study area was the steep terrain, which further hampered visibility and communication. Even though the take-off sites were located high on the ridges, the drone sometimes became obscured in the lower parts of the slopes. Such challenges in mountainous areas with dense canopy forests should be accounted for during survey planning.

Deer densities estimated separately for each of the three habitat categories were much lower in the forest than in the shrubs and grasslands (Table 2). This was expected not only due to the lower detection probability in forests caused by leaf cover, but primarily because the surveys were started at dusk, when deer move from forests to open habitats to forage.

During the study, we attempted to test whether the camera mounting angle affects animal detection in forested areas. With oblique views (angle > 0°), the crown layer obscuring the animals is expected to be thicker than when the camera is pointing directly downward. We conducted two survey repetitions with camera angles of 40° and 0° in the Grandes Fougères study area. However, the number of deer detected within the forest land cover class (4 animals in the 40° survey and

4 in the 0° survey) was too small a sample size to verify our hypothesis about the role of camera angle in the detection process. Nevertheless, we observed another problem related to the oblique camera angle in steep terrain – when the drone flies downslope, the distance between the camera and the center of the observed area is much longer than over flat terrain. This reduces image resolution and may decrease the probability of animal identification. The issue is minimized when the camera is oriented directly downward. Therefore, for surveys in steep mountainous areas, we recommend setting the camera at a 0° angle.

Surveys over each sampling block were repeated to assess the variability of the counts. The observed small differences in deer numbers detected during consecutive surveys were most likely due to animal movement. This is supported by the positive correlation between the percentage of absolute change in counts and the time gap between repeated flights. Longer intervals (up to 100 minutes) allowed some animals to leave or enter the surveyed strip. Given the stable weather conditions, changes in detection probability due to weather were unlikely. These minor differences in deer numbers had no significant effect on relative density estimates for the entire area. The general consistency of estimates derived from consecutive flights indicates that drone surveys are highly repeatable, making this method well suited for population monitoring.

Wildlife surveys using drones may be affected by animals' response to the aircraft (Ditmer et al. 2015; Mulero-Pázmány et al. 2017). Deer disturbed by the drone could move out of the surveyed area, shift between transects, or seek shelter under trees, leading to bias and increased variability in counts. However, we did not observe any reaction of deer to the drone flying at various altitudes, either during the preliminary test flights at the hunting farm or in the wilderness survey areas. Only a small fraction (~6%) of deer were recorded while walking or running, and no consistent movement pattern was apparent. Therefore, we assume that the 10 m spacing between filmed strips was sufficient to minimize the risk of double-counting. The lack of deer reaction to the drone is in line with observations made by Zabel et al. (2023) during drone surveys of red deer (*Cervus elaphus*) in Germany. Nevertheless, the potential disturbance of animals should be considered during survey planning, as other species may be more sensitive to drone operations.

The effectiveness of any population monitoring program depends on its ability to detect differences between consecutive estimates or long-term trends. The observed substantial spatial variability in deer distribution – where deer counts among the sampling blocks differed by more than 10-fold – decreases the precision of the density estimates and the power to detect trends. In Déva, with 10 sampling blocks surveyed, a 25% population decline could be detected with a power of 0.8 (Fig. 7). This level of power to detect change is sufficient, considering that the deer management strategy for New Caledonia aims for over 25% reduction in deer numbers. In contrast, in the rainforests of Grandes Fougères, the low encounter rate (number of deer detected per kilometer of transect) resulted in low power to detect trends – about 28 sampling blocks would be needed to detect a 25% population decline. The smaller the change in population density we wish to detect, the greater the number of sampling blocks required. When monitoring goals are clearly defined – i.e., the magnitude of population change to be detected – power analysis can be used to determine the appropriate number of sampling blocks needed. This approach is necessary to optimize monitoring costs and achieve meaningful results.

Wildlife monitoring in remote and undeveloped areas with limited road systems is challenging. Our experience indicates that it is possible to survey about six sampling blocks (50–90 ha each) in a single night. This requires six sets of batteries weighing approximately 18 kg along with two transport cases. An additional case with the drone and other equipment weighs about 14 kg. Since this total weight can be carried by people or on horseback, surveys can be conducted even in areas without vehicle access. The batteries can be recharged at the parking spot using a vehicle-mounted power generator, which further simplifies survey logistics in remote locations. When single surveys are conducted over each sampling block, it takes on average three nights to survey 18 sampling blocks – enough to achieve the power to detect even a 20% reduction in population size. This indicates that the method would be effective for monitoring deer populations in remote areas, such as the mountain rainforest priority zones.

Advantages of the method

An important advantage of drone surveys is that the acquired data are verifiable – the recorded videos can be stored, reviewed, and reanalyzed if needed. This is particularly valuable in situations where local stakeholders – such as hunters, farmers, and conservation activists – have conflicting interests. These groups may have limited trust in data from indirect surveys (e.g., pellet counts, browsing indices), as such data are difficult to translate into actual deer numbers. In contrast, drone-acquired data – video recordings showing herds of deer from the air – are more illustrative, convincing, and easier to interpret. The strength of visual evidence in this context is difficult to overstate. For example, landowners, local tribal customary authorities, residents, and neighbors of the priority zones who have access to such "hard data" can better assess the potential benefits of deer harvesting and are more likely to accept professional deer control actions.

Another advantage is that the video files acquired from drones are georeferenced, and habitat variables (e.g., land cover classes, altitude above sea level) can be easily derived from GIS data layers and linked to deer detections. In the future, when data for multiple years become available, population dynamics could be modeled more precisely using habitat covariates. This is particularly important in situations where an entirely random selection of survey sites is impossible due to difficulties in access. Developing deer habitat-use models offers an opportunity to better understand their spatial distribution and to predict densities in non-surveyed regions of the island, leading to more effective population management (Hess et al. 2023).

One of the main goals of wildlife monitoring is to detect population responses to management actions, which requires data from surveys conducted over multiple years. High-quality data can only be gathered if the survey protocol is fully reproducible over time. Drones offer an exceptional level of reproducibility, as the same flight paths and parameters, such as altitude, speed, and camera angle, can be easily replicated in future surveys. Applying these settings, along with conducting surveys at the same time of year and day, minimizes variability due to survey conditions. Furthermore, the use of artificial intelligence algorithms for detecting and counting animals in recorded video files would eliminate human errors, provide an additional level of standardization, and reduce the time and cost of data analysis (Eikelboom et al. 2019; Delplanque et al. 2024).

Aerial thermography can be recorded as video files or still images. Our experience from the current study, as well as from previous research (Witczuk et al. 2018; Pagacz and Witczuk 2023), indicates that video data offer significant advantages. The movement of animals captured on video helps distinguish their thermal signatures from other similarly sized hot objects, thereby aiding in detection and recognition. Additionally, video recorded at 30 frames per second – compared to the typical one image per second for still imagery – offers a higher probability of detecting animals, particularly in forested areas, by capturing multiple views of a given location from shifting drone perspectives. It is also important that video footage allows observation of animals' responses to the drone and the direction of their movement, which – if not random – may lead to biased population estimates.

Limitations

Drone-based surveys proved to be less effective in dense canopy rainforests than in open areas. In New Caledonia, however, this limitation is less significant, as rainforests cover only about 20% of the island (Allenbach 2021), while shrubs and grasslands account for over 55% (Gouvernement de la Nouvelle-Calédonie and Observatoire de l'Environnement en Nouvelle-Calédonie 2019). To enhance survey effectiveness in mountainous rainforest priority zones, we recommend planning sampling blocks in areas where closed-canopy forest cover does not exceed 50% and allocating greater sampling effort to adjacent savanna areas where deer tend to congregate for foraging.

Thermal drone survey limitations also relate to the technical aspects of data analysis. The videos captured during our surveys were manually reviewed using an open-source FMV plug-in for QGIS. This software is basic and lacks several useful features. For instance, while it is possible to create a GIS point layer indicating deer locations by selecting points in the video display window, it is not possible to simultaneously assign attributes such as group size or animal behavior. These attributes must be entered and saved externally in spreadsheet software, which is both time-consuming and prone to errors. The time required to review a video of approximately 40 minutes (recorded over an average-sized sample block of about 70 ha) ranges from 60 to 90 minutes, depending on the number of deer detected and the operator's experience. The procedure is highly fatiguing, making it difficult to review more than two video files consecutively. The solution would be an automatic video analysis using deep learning algorithms (Sudholz et al. 2021). While commercially available software enabling object detection and tracking in a geographic context is limited and expensive (e.g., the FMV for ArcGIS Pro from ESRI), developing new, original software requires time and the employment of highly qualified personnel. In any case, it is first necessary to create a database for training, testing, and validating the detection/classification algorithm. The data collected during this study provide a good starting point for building such a database and also offer an opportunity to develop a first version of the algorithm, laying the groundwork for future investment in its development. Upcoming deer surveys in New Caledonia are expected to be analyzed using deep learning algorithms, which should significantly reduce the time required for data analysis.

The low resolution of commonly used thermal sensors (640 × 512 pixels) is another limiting factor. To achieve an acceptable level of detail in the obtained images, the flight altitude must be relatively low (≤ 100 m), which limits the strip width and reduces the efficiency of the surveys. However, recently introduced high-resolution thermal cameras (1280 × 1024) offer the possibility of increasing the flight altitude without the cost of detail loss. Additionally, flying at higher altitudes may help overcome communication issues caused by the terrain, thereby extending the effective range of drone surveys. It is only a matter of time before high-resolution cameras become standard in wildlife research, elevating the quality of drone-acquired thermal imaging to an entirely new level.

The final limiting factor is regulations. After years of constant changes, regulations regarding the use of drones are now well established. However, to ensure the safety of all airspace users, the rules for drone operations remain quite restrictive. In most cases, conducting nighttime wildlife surveys will require holding a professional drone pilot license and applying for exemptions that allow night operations at the desired altitude or distance. These regulatory procedures can be cumbersome, depending on the location and the applicant's experience. Therefore, wildlife managers planning drone surveys should be aware that obtaining the necessary permits can be time-consuming. The high requirements for drone operators, combined with the high cost of the equipment, mean that stakeholders will usually not be able to conduct surveys independently. Instead, they will need to outsource the service to a well-equipped and experienced external contractor.

Conclusion

Drones equipped with thermal cameras are an effective tool for assessing the relative density of invasive Javan deer in the challenging landscapes of New Caledonia. The time efficiency, verifiability of the data, and highly reproducible survey protocol make drone surveys a much better option than alternative ground-based methods. The straightforward interpretation of the data and the strong demonstrative value of the videos facilitate social acceptance of deer management actions – especially professional deer control – by local stakeholders, such as landowners, residents, tribal customary authorities, and politicians. Further improvements to the method will require the development of software for automatic video analysis and the use of high-resolution thermal cameras.

Acknowledgments

We are grateful to Patrick Barrière, Marco Zaccaroni, and an anonymous reviewer for their valuable comments and edits on the first draft of the manuscript. This study was carried out as part of the PROTEGE project (Pacific Territories Regional Project for Sustainable Ecosystem Management). We thank the team at the Agence néo-Calédonienne de la Biodiversité (ANCB), responsible for implementing PROTEGE project actions in New Caledonia concerning invasive ungulates, in particular Carole Wéma, Géraldine Bidau, Maxime Lebouteiller, and Patrick Barrière. We also acknowledge the ANCB's "Invasive Ungulates" technical group, which serves as the PROTEGE project's steering committee for issues related to invasive deer, feral pigs, and feral goats. Our thanks extend to the Pacific Community (SPC) and the Secretariat of the Pacific Regional Environment Programme (SPREP), the delegatee and co-delegatee of the PROTEGE project, respectively. We also wish to thank Jocelyn Amice, Director of SEM Mwé Ara at the Domaine de Déva; Christophe Schall, Manager of Parc provincial des Grandes Fougères; and Philippe Bourgine, owner of the hunting and cattle farm La Cotonnière.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

Funding

The research was conducted under the PROTEGE framework (Pacific Territories Regional Project for Sustainable Ecosystem Management, Theme 4 "Invasive Alien Species," https://protege.spc.int/fr) and financed by the European Union under the 11th Regional European Development Fund (EDF), the New Caledonian "Agence Rurale," and the provincial authorities.

Author contributions

Julia Witczuk: conceptualization; formal analysis; investigation; methodology; writing – original draft (lead); writing – review and editing, visualization

Stansław Pagacz: conceptualization; data curation; formal analysis; investigation; methodology; writing – original draft; writing – review and editing; visualization.

Romain Alliod: conceptualization; data curation; funding acquisition; investigation; methodology; resources.

Author ORCIDs

Julia Witczuk https://orcid.org/0000-0003-0808-1768

Stanisław Pagacz https://orcid.org/0000-0002-0650-9575

Data availability

All of the data that support the findings of this study are available in the main text.

References

Allenbach M (2021) The natural environment of New Caledonia. In: Gravelat C (Ed.) Understanding New Caledonia. University Presses of New Caledonia, Nouméa, New Caledonia, 37–48. https://unc.nc/understanding-new-caledonia/

Baldwin RW, Beaver JT, Messinger M, Muday J, Windsor M, Larsen GD, Silman MR, Anderson TM (2023) Camera trap methods and drone thermal surveillance provide reliable, comparable density estimates of large, free-ranging ungulates. Animals (Basel) 13(11): 1884. https://doi.org/10.3390/ani13111884

Barrière P, Fort C (2021) Rusa timorensis (de Blainville, 1822). In: Savouré-Soubelet A, Arthur C, Aulagnier S, Body G, Callou C, Haffner P, Marchandeau S, Moutou F, Saint-Andrieux C (Eds) Atlas des mammifères sauvages de France, vol 2 Ongulés et Lagomorphes. Muséum National d'Histoire Naturelle, Paris, 96–101.

Barry J, Maxwell D (2017) emon: Tools for environmental and ecological survey design. R package version 1.3.2. Comprehensive R Archive Network (CRAN). https://CRAN.R-project.org/package=emon

Beaver JT, Baldwin RW, Messinger M, Newbolt CH, Ditchkoff SS, Silman MR (2020) Evaluating the use of drones equipped with thermal sensors as an effective method for estimating wildlife. Wildlife Society Bulletin 44(2): 434–443. https://doi.org/10.1002/wsb.1090

Bouchet P, Jaffre T, Veillon J-M (1995) Plant extinction in New Caledonia: Protection of sclerophyll forests urgently needed. Biodiversity and Conservation 4(4): 415–428. https://doi.org/10.1007/BF00058425

Bowen L, Van Vuren D (1997) Insular endemic plants lack defenses against herbivores. Conservation Biology: The Journal of the Society for Conservation Biology 11(5): 1249–1254. https://doi.org/10.1046/j.1523-1739.1997.96368.x

Burke C, Rashman M, Wich S, Symons A, Theron C, Longmore S (2019) Optimizing observing strategies for monitoring animals using drone-mounted thermal infrared cameras. International Journal of Remote Sensing 40(2): 439–467. https://doi.org/10.1080/01431161.2018.1558372

Comte S, Thomas E, Bengsen AJ, Bennett A, Davis NE, Freney S, Jackson SM, White M, Forsyth DM, Brown D, Taylor A (2022) Seasonal and daily activity of non-native sambar deer in and around high-elevation peatlands, south-eastern. Wildlife Research 49(7): 659–672. https://doi.org/10.1071/WR21147

Conservation International, Conservatoire d’espaces naturels de Nouvelle-Calédonie (2016) Eléments de cadrage pour une stratégie de régulation des cerfs en Nouvelle Calédonie: zones prioritaires, vision, objectifs et ressources nécessaires. Nouvelle-Calédonie, 70 pp.

Conservatoire d’espaces naturels de Nouvelle-Calédonie (2017) Stratégie de lutte contre les espèces exotiques envahissantes dans les espaces naturels de Nouvelle-Calédonie. Document cadre. 107 pp. https://especes-envahissantes-outremer.fr/wp-content/uploads/2018/03/strategie-de-lutte-contre-les-eee-en-nouvelle-caledonie-2017.pdf

Courchamp F, Chapuis JL, Pascal M (2003) Mammal invaders on islands: Impact, control and control impact. Biological Reviews of the Cambridge Philosophical Society 78(3): 347–383. https://doi.org/10.1017/S1464793102006061

de Garine-Wichatitsky M, Saint-Andrieux C (2003) Faisabilité des méthodes de suivi-évaluation des populations de cerf rusa (*Cervus timorensis russa*) en Nouvelle-Calédonie. Institut Agronomique néo-Calédonien, Païta, Nouvelle-Calédonie, 42 pp.

de Garine-Wichatitsky M, Spaggiari J (2008) Alien plants in native sclerophyll forests of New Caledonia: the role of ungulates. In: Blanfort V, Orapa W (Eds) Ecology, impacts and management of invasive plant species in pastoral areas: Proceedings of the Regional workshop on invasive plant species in pastoral areas, Koné (New Caledonia), November 2003. Secretariat of the Pacific Community, Koné, Nouvelle-Calédonie, 80–84.

de Garine-Wichatitsky M, Chardonnet P, de Garine I (2004) Management of introduced game species in New Caledonia: Reconciling biodiversity conservation and resource use? Game and Wildlife Science 21: 697–706.

Delplanque A, Linchant J, Vincke X, Lamprey R, Théau J, Vermeulen C, Foucher S, Ouattara A, Kouadio R, Lejeune P (2024) Will artificial intelligence revolutionize aerial surveys? A first large-scale semi-automated survey of African wildlife using oblique imagery and deep learning. Ecological Informatics 82: 102679. https://doi.org/10.1016/j.ecoinf.2024.102679

Ditmer MA, Vincent JB, Werden LK, Tanner JC, Laske TG, Iaizzo PA, Garshelis DL, Fieberg JR (2015) Bears show a physiological but limited behavioral response to unmanned aerial vehicles. Current Biology : CB 25(17): 2278–2283. https://doi.org/10.1016/j.cub.2015.07.024

Eikelboom JAJ, Wind J, van de Ven E, Kenana LM, Schroder B, de Knegt HJ, van Langevelde F, Prins HHT (2019) Improving the precision and accuracy of animal population estimates with aerial image object detection. Methods in Ecology and Evolution 10(11): 1875–1887. https://doi.org/10.1111/2041-210X.13277

Finnegan SP, Hinojo A, Monod S, Wall WA, Olsen P, Allen ML (2024) A comparison of thermal drones and camera trap population estimates for Sitka black-tailed deer in Alaska. Wildlife Biology n/a: e01360. https://doi.org/10.1002/wlb3.01360

Fort C, Barrière P (2021) Monographie géographique sur la Nouvelle-Calédonie. In: Savouré-Soubelet A, Arthur C, Aulagnier S, Body G, Callou C, Haffner P, Marchandeau S, Moutou F, Saint-Andrieux C (Eds) Atlas des mammifères sauvages de France, vol 2 Ongulés et Lagomorphes. Muséum National d'Histoire Naturelle, Paris, 248–253.

Fotsing J-M, Dumas P (2021) The physical and human geography of the New Caledonian archipelago. In: Understanding New Caledonia. University Press of New Caledonia Nouméa, Nouméa, New Caledonia, 19–36. https://unc.nc/understanding-new-caledonia/

Gargominy O, Bouchet P, Pascal M, Jaffre T, Tourneur J-C (1996) Conséquences des introductions d'espèces animales et végétales sur la biodiversité en Nouvelle-Calédonie. Revue d'Écologie 51: 375–402. https://doi.org/10.3406/revec.1996.2217

Gouvernement de la Nouvelle-Calédonie, Observatoire de l'Environnement en Nouvelle-Calédonie (2019) Occupation du sol 2014 au format Shapefile [Dataset]. DINUM / Service de la Géomatique et Télédétection. https://sig-public.gouv.nc/plateforme_telechargement/MOS2014_PN_PS_PI_SHP.zip [accessed 29.05.2020]

Hess SC, Berio Fortini L, Leopold CR, Muise J, Sprague JC (2023) Ecological associations of non-native ungulates on the Hawaiian Island of Lāna'i. Human-Wildlife Interactions 17: 230–243. https://doi.org/10.26077/be03-b519

IPBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany, 56 pp. https://doi.org/10.5281/zenodo.3553579

Isnard S, Jaffré T (2024) What makes New Caledonia's flora so outstanding? In: Kowasch M, Batterbury SPJ (Eds) Geographies of New Caledonia-Kanaky: Environments, Politics and Cultures. Springer International Publishing, Cham, 21–32. https://doi.org/10.1007/978-3-031-49140-5_3

Kingsford RT, Watson JEM, Lundquist CJ, Venter O, Hughes L, Johnston EL, Atherton J, Gawel M, Keith DA, Mackey BG, Morley C, Possingham HP, Raynor B, Recher HF, Wilson KA (2009) Major conservation policy issues for biodiversity in Oceania. Conservation Biology: The Journal of the Society for Conservation Biology 23(4): 834–840. https://doi.org/10.1111/j.1523-1739.2009.01287.x

Le Bel S, Brescia F, Barré N (1999) Etude de la biologie du cerf rusa (*Cervus timorensis russa*) en milieu naturel, base d'un plan de gestion des populations de cervidés sauvages. Étude de cas: La propriété Metzdorf sur la côte Ouest de la Nouvelle-Calédonie. CIRAD-EMVT, Port-Laguerre, Nouvelle-Caledonie, 63 pp.

Le Bel S, Sarrailh JM, Brescia F, Cornu A (2001) Présence du cerf rusa dans le massif de l'Aoupinié en Nouvelle-Calédonie et impact sur le reboisement en kaoris: Gestion de la faune. Bois et Forêts des Tropiques 269: 5–17. https://revues.cirad.fr/index.php/BFT/article/view/20092

Lefeuvre J-C (2006) Les invasions biologiques: un risque pour la biodiversité à l'échelle mondiale. In: Beauvais M-L, Coléno A, Jourdan H (Eds) Les espèces envahissantes dans l'archipel néo-calédonien. IRD Éditions, Paris, CD–ROM: 4–49. https://doi.org/10.4000/books.irdeditions.7656

Mansourian S, Géraux H, Do Khac E, Vallauri D (2018) Lessons learnt from 17 years of restoration in New Caledonia's dry tropical forest. WWF France, 42 pp.

McMahon MC, Ditmer MA, Isaac EJ, Moore SA, Forester JD (2021) Evaluating unmanned aerial systems for the detection and monitoring of moose in northeastern Minnesota. Wildlife Society Bulletin 45(2): 312–324. https://doi.org/10.1002/wsb.1167

McMahon MC, Ditmer MA, Forester JD (2022) Comparing unmanned aerial systems with conventional methodology for surveying a wild white-tailed deer population. Wildlife Research 49(1): 54–65. https://doi.org/10.1071/WR20204

Mittermeier R, Gil P, Hoffmann M, Pilgrim J, Brooks T, Mittermeier C, Lamoreux J, Fonseca G (2004) Hotspots Revisited. Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions. CEMEX, Mexico City, Mexico, 392 pp.

Morat P (1993) Our knowledge of the flora of New Caledonia: Endemism and diversity in relation to vegetation types and substrates. Biodiversity Letters 1(3/4): 72–81. https://doi.org/10.2307/2999750

Mulero-Pázmány M, Jenni-Eiermann S, Strebel N, Sattler T, Negro JJ, Tablado Z (2017) Unmanned aircraft systems as a new source of disturbance for wildlife: A systematic review. PLoS One 12(6): e0178448. https://doi.org/10.1371/journal.pone.0178448

Munzinger J, Morat P, Jaffré T, Gâteblé G, Pillon Y, Rouhan G, Bruy D, Veillon J-M, Chalopin M (2025) FLORICAL: checklist of the vascular indigenous flora of New Caledonia. http://publish.plantnet-project.org/project/florical [accessed 31.03.2025]

Myers N (1988) Threatened biotas: "Hot spots" in tropical forests. The Environmentalist 8(3): 187–208. https://doi.org/10.1007/BF02240252

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403(6772): 853–858. https://doi.org/10.1038/35002501

Pacific Community (2025) PROTEGE: Pacific Territories Regional Project for Sustainable Ecosystem Management. https://protege.spc.int/en [accessed 01.05.2025]

Pagacz S, Witczuk J (2023) Estimating ground surface visibility on thermal images from drone wildlife surveys in forests. Ecological Informatics 78: 102379. https://doi.org/10.1016/j.ecoinf.2023.102379

R Core Team (2025) R: A language and environment for statistical computing. https://www.R-project.org/ [accessed 01.05.2025]

Raga F (2021) QGIS Full Motion Video version 1.15. https://github.com/All4Gis/QGISFMV [accessed 01.05.2025]

Roques-Rogery G (2008) Monitoring population trends of introduced rusa deer (*Cervus timorensis russa*) in New Caledonian sclerophyll forests: tests and relevance of methods for management programmes. MS Thesis. Nelson Mandela Metropolitan University (Port Elizabeth, RSA), 88 pp.

Russell JC, Kueffer C (2019) Island biodiversity in the Anthropocene. Annual Review of Environment and Resources 44(1): 31–60. https://doi.org/10.1146/annurev-environ-101718-033245

Sudholz A, Denman S, Pople A, Brennan M, Amos M, Hamilton G (2021) A comparison of manual and automated detection of rusa deer (*Rusa timorensis*) from RPAS-derived thermal imagery. Wildlife Research 49(1): 46–53. https://doi.org/10.1071/WR20169

Tramier CMC, Genthon P, Delvienne QRCP, Sauvan NL, Cassan JJO, Ebrard E, Dumas PS, Queffélean Y (2021) Hydrological regimes in a tropical valley of New Caledonia (SW Pacific): Impacts of wildfires and invasive fauna. Hydrological Processes 35(3): e14071. https://doi.org/10.1002/hyp.14071

Trinh-Dinh H, Wearn OR, Ngoprasert D, Wich S, Savini T (2024) A drone-based population survey of Delacour's langur (*Trachypithecus delacouri*) in the karst forests of northern Vietnam. Biological Conservation 300: 110841. https://doi.org/10.1016/j.biocon.2024.110841

Tron F, Brisset M, Haverkamp C, Barrière R, Aubert M, Theuerkauf J (2024) Exclosure from browsing by invasive ungulates increases species richness and diversity of ground flora in rainforests of New Caledonia. Biological Conservation 296: 110675. https://doi.org/10.1016/j.biocon.2024.110675

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science 277(5325): 494–499. https://doi.org/10.1126/science.277.5325.494

Witczuk J, Pagacz S, Zmarz A, Cypel M (2018) Exploring the feasibility of unmanned aerial vehicles and thermal imaging for ungulate surveys in forests - preliminary results. International Journal of Remote Sensing 39(15–16): 5504–5521. https://doi.org/10.1080/01431161.2017.1390621

World Bank (2025) Current Climate: New Caledonia. Climate Change Knowledge Portal. https://climateknowledgeportal.worldbank.org/ [Accessed April 11, 2025]

Zabel F, Findlay MA, White PJC (2023) Assessment of the accuracy of counting large ungulate species (red deer *Cervus elaphus*) with UAV-mounted thermal infrared cameras during night flights. Wildlife Biology 2023(3): e01071. https://doi.org/10.1002/wlb3.01071